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Evaluation of Yield Traits and Correlation Analysis for Screening Waterlogging-Tolerant Soybean (*Glycine max* L.) Genotypes

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Abstract

Soybean (*Glycine max* L.) is a major oilseed crop valued for its nutritional composition and its role in sustainable agriculture. In rainfed regions like Madhya Pradesh, waterlogging due to erratic monsoon rainfall significantly limits soybean productivity. This study aimed to identify waterlogging-tolerant soybean genotypes through integrated evaluation of yield traits and correlation analysis. The experiment was conducted during the Kharif season (2023–24) at the Demonstration cum Experimental Farm of Shri Vaishnav Institute of Agriculture, SVVV, Indore, using 45 genotypes in a randomized block design with two replications. Seeds were sown by dibbling, and standard agronomic practices were followed under simulated waterlogged conditions. Traits including number of pods per plant, number of seeds per pod, 100-seed weight, seed yield, biological yield, and harvest index were recorded. Correlation analyses (Pearson and Spearman) revealed significant associations of seed yield with pod number, seed weight, and plant height. Genotypes NRC 258, JS 21-72, AMS 2014-1, and RVSM 2011-35 exhibited superior yield performance and resilience. Mahalanobis D^2 inter-cluster analysis showed maximum genetic divergence between Cluster III and Cluster IV, indicating potential for heterotic breeding. Combining phenotypic screening, correlation metrics, and multivariate clustering provides a strategy for selecting waterlogging-tolerant soybean genotypes suitable for stress-prone agro-ecologies.

Key words : Soybean genotypes, Waterlogging tolerance, Yield traits, Correlation analysis, Cluster analysis.

Soybean (*Glycine max* L. Merrill) is a globally significant oilseed crop, valued for its dual-purpose composition approximately 40% protein and 20% oil making it indispensable for human nutrition, animal feed, and various industrial applications (Hartman *et al*., 2011). Its agronomic importance extends beyond nutritional output, as soybean significantly contributes to sustainable farming systems through its symbiotic nitrogen-fixing ability, which enriches soil fertility and supports crop rotations (Hungria & Mendes, 2015).

In countries like India, soybean cultivation plays a critical role in supporting rural livelihoods, agro-industrial development, and national food and economic security. Madhya Pradesh, often called the "Soy State," contributes over 50% of India's soybean production, with a cultivated area exceeding 6 million hectares (Directorate of Economics and Statistics, 2023). Districts including Indore, Dhar, Sehore, and Ujjain are major soybean-growing regions. Despite its prominence, the average productivity in India remains suboptimal at approximately 1,043 kg ha^{-1}, far below the global average of 2,500 kg ha^{-1} (FAO, 2022). One of the main abiotic stresses responsible for this yield gap is waterlogging, particularly during the monsoon season. This stress adversely affects soybean physiology by inhibiting root respiration, reducing nutrient and water uptake, impairing photosynthesis, and ultimately resulting in substantial yield losses (Xiong *et al*., 2021).

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Genetic improvement for waterlogging tolerance is a sustainable and long-term approach to overcoming this constraint. Phenotypic evaluation under waterlogged conditions allows for the identification of tolerant genotypes based on key traits such as number of pods per plant, number of seeds per pod, 100-seed weight, seed yield, biological yield, and harvest index. These traits serve as critical indicators of genotypic performance under stress (Ikram *et al*., 2022). Correlation analysis techniques like Pearson's and Spearman's rank correlation further enhance selection accuracy by revealing interrelationships among traits. A positive correlation between 100-seed weight and seed yield under waterlogging highlights the role of efficient assimilate partitioning (Zaman, 2019). Multivariate cluster analysis using Mahalanobis D^2 distances helps determine genetic divergence among genotypes, which is essential for selecting diverse parents in hybridization programs (Mounika *et al*., 2022).

In this study, 45 soybean genotypes were systematically evaluated under controlled waterlogged conditions to identify high-yielding and tolerant lines. The integrated approach involving field-based trait analysis, statistical correlation, and inter-cluster distance assessment provides a comprehensive framework for understanding waterlogging tolerance. The results are expected to support the development of climate-resilient soybean cultivars tailored to the agro-ecological conditions of Madhya Pradesh and similar regions. This aligns with India's strategic goals of oilseed self-reliance, crop stabilization, and promotion of precision agriculture in vulnerable farming systems.

Materials and Methods

The present investigation entitled "Evaluation of soybean genotypes for waterlogging tolerance" was conducted during the Kharif season (2023–24) at the Demonstration cum Experimental Farm, Shri Vaishnav Institute of Agriculture, SVVV, Indore. The site experienced moderate temperature fluctuations (23.07°C-31.15°C maximum and 13.93°C-16.20°C minimum), high relative humidity (56.75%-90.43% in mornings), variable wind speeds (2.93-5.87 km hr^{-1}), sunshine duration (4.77-8.97 hours), and a seasonal rainfall of 15.2 mm. The experiment was laid out in a Randomized Block Design (RBD) with two replications and included 45 soybean genotypes sourced from IISR Indore, College of Agriculture Indore (RVSKVV), MACS-ARI Pune, and ARS Kasbe Digraj. Sowing was done by dibbling on July 15, 2024, with a spacing of 30 x 10 cm and a fertilizer dose of 00:50:75 NPK (kg ha^{-1}). Standard intercultural operations like gap filling and thinning were carried out 15 days after sowing. Observations were recorded on several yield and stress-related parameters, including number of pods $plant^{-1}$, number of seeds pod^{-1}, 100-seed weight, plant survival rate, stress tolerance index, seed yield $plant^{-1}$, biological yield $plant^{-1}$, and harvest index. Seed yield was derived from five sampled plants $plot^{-1}$, and harvest index was calculated as a ratio of grain yield to total biomass. For trait association analysis, Pearson and Spearman's rank correlation coefficients were computed among 15 agro-morphological, physiological, and biochemical traits under waterlogged conditions. Statistical analysis was carried out using methods appropriate for RBD as outlined by Gomez and Gomez (1984) to determine the significance of genotypic differences and interrelationships among traits.

Result and Discussion

Soybean Genotypes for Yield Traits Under Waterlogging : The evaluation of 45 soybean genotypes under waterlogging stress showed notable variation in three key yield traits: number of pods $plant^{-1}$, number of seeds pod^{-1}, and 100-seed weight (Table 1). The number of pods plant^{-1} ranged from 36 (IC0501649) to 47 (NRC 260, AMS 2021-3), with genotypes like NRC 258, JS 97-52, and NRC 142 also showing high pod numbers. This suggests a strong ability of these genotypes to sustain reproductive growth under stress, likely due to better root aeration and nutrient translocation (MEENA, 2013). The number of seeds per pod varied narrowly between 2.2 and 2.4, with genotypes EC0041323, Raj Soya 18, JS 24-26, and JS 95-60 recording the maximum (2.4). Although this trait was less variable, it remains important for maintaining yield under stress conditions (Soni, 2021). The 100-seed weight ranged widely from 10.2 g to 13.7 g. NRC 258 and MAUS-814 exhibited the highest seed weight (13.7 g), followed by RVSM 2011-35, JS 95-60, and AMS 2014-1. Higher seed weight reflects better assimilate partitioning and stress tolerance (Iqbal *et al.*, 2018). Genotypes NRC 258, NRC 260, RVSM 2011-35, JS 95-60, and AMS 2021-3 emerged as superior, combining higher pod number, adequate seed set, and excellent seed mass. These traits are crucial for waterlogging resilience and should be prioritized in breeding programs aimed at improving soybean performance under adverse conditions (Chandra *et al.*, 2022).

Soybean Genotypes for Yield and Harvest Index Under Waterlogging : The analysis of seed yield plant^{-1}, biological yield plant^{-1}, and harvest index among 45 soybean genotypes under waterlogging stress revealed considerable genotypic variability (Table 2). These traits are crucial indicators of a genotype's productivity and efficiency in converting biomass into economic yield under adverse conditions. Seed yield plant^{-1} ranged from 9.1 g (IC0243788, IC0118237) to 15.8 g (NRC 127), with NRC 258 (15.5 g), JS 21-72 (14.8 g), NRC 142 (14.5 g), and AUKS212 (14.5 g) also demonstrating high yield potential. The superior performance of these genotypes under

Table 1. Evaluation of soybean genotypes for water logging tolerance on Number of Pods Plant^{-1}, Number of Seeds Pod^{-1}, 100-Seed Weight (g)

Genotype	No. of pods plant^{-1}	No. of seeds pod^{-1}	100-seed weight (g)
IC241807	39	2.2	11.6
EC389174	38	2.3	10.2
IC0243788	37	2.2	11.2
EC0041323	40	2.4	11.3
IC0501649	36	2.2	10.9
IC597390	40	2.3	11.2
EC0014461	40	2.3	12.1
IC243703	38	2.3	10.8
IC0243746	40	2.2	11.7
IC0243102	40	2.3	11.3
IC0118394	39	2.3	12.1
EC0481457	40	2.2	11.8
IC0629156	40	2.3	10.5
IC243079	37	2.3	10.5
EC250601	40	2.2	10.5
IC012003	40	2.3	12.7
IC0118237	39	2.3	10.5
IC0243068	40	2.3	10.5
IC0243809	41	2.2	10.5
IC0014479	40	2.3	10.5
NRC 138	38	2.3	11.6
NRC 127	38	2.3	11.8
JS 97-52	46	2.3	10.5
NRC 142	45	2.3	13.1
Raj Soya 18	45	2.4	10.8
NRC 258	46	2.3	13.7
NRC 260	47	2.2	12.8
MACS 1407	45	2.3	12.7
MACS 1188	39	2.4	10.5
JS 24-26	42	2.4	11.5
KDS 992	40	2.2	11.8
RVSM 2011-35	42	2.3	13.3
AMS 2021-3	47	2.3	10.8
AMS 2021-4	45	2.2	10.2
AMS 2014-1	38	2.3	12.9
AS 55	39	2.2	10.8
MAUS-814	37	2.2	13.7
AUKS212	40	2.3	10.5
DS 1570	40	2.3	10.5
RSC 1172	42	2.3	12.5
ASB 85	40	2.2	10.4
RVS 12-8	38	2.3	10.8
PS 26	40	2.3	10.5
JS 95-60	37	2.4	13.3
JS 21-72	45	2.3	12.4
SE(m)±	1.334	0.031	0.106
CV	4.652	1.917	1.313
CD	3.815	0.088	0.304

stress suggests enhanced assimilate allocation to reproductive sinks and improved physiological resilience. High-yielding lines under waterlogged conditions likely possess traits such as deeper root systems and effective oxygen transport, which sustain pod development despite hypoxia (Singh *et al*., 2022).). Biological yield per plant, representing total biomass production, ranged from 29 g (IC0243102) to 49 g (NRC 127, MACS 1188, NRC 142). Genotypes with high biological yield, such as NRC 127, NRC 142, MACS 1188, and JS 95-60, reflect better vegetative growth and resource acquisition under stress. A high biological yield does not always equate to a higher seed yield unless the harvest index is also favourable (Kanwar, 2016). Harvest index (HI), which measures the efficiency of converting total biomass into grain, varied from 27.1% (EC0481457) to 33.0% (NRC 258), with other top-performing genotypes including NRC 127 (32.9%), AMS 2014-1 (32.4%), and RVSM 2011-35 (32.2%). A higher HI under stress conditions indicates genotypes with superior partitioning ability, favouring reproductive output over vegetative mass (Asefa, 2019). NRC 258, NRC 127, JS 21-72, AMS 2014-1, and RVSM 2011-35 emerged as the most promising genotypes, showing high seed yield, balanced biological yield, and excellent harvest index. These genotypes possess the ideal combination of traits for performance under waterlogged environments and should be prioritized in breeding programs targeting stress tolerance.

The Pearson correlation analysis : The Pearson correlation analysis among various agro-morphological and biochemical traits in 45 soybean genotypes under waterlogging stress revealed several significant interrelationships that are useful for selection and breeding strategies (Table 3). A strong positive correlation was observed between days to 50% flowering and days to physiological maturity ($r = 0.875^{**}$), indicating synchrony in crop development stages. This is important for determining genotype adaptability to stress-prone environments (Concenco *et al*., 2014). Plant height showed significant positive correlation with number of pods per plant ($r = 0.354^{*}$) and 100-seed weight ($r = 0.368^{*}$), suggesting that taller plants had better reproductive success and seed development under waterlogging. Similar associations have been reported by Azmat *et al*. (2024), highlighting that vigorous vegetative growth can support yield resilience under abiotic stress. Seed yield per plant showed highly significant positive correlations with number of pods per plant ($r = 0.387^{**}$), number of seeds per pod ($r = 0.321^{*}$), and 100-seed weight ($r = 0.500^{**}$), confirming these traits as major contributors to yield under stress. These findings align with those of Singh *et al*. (2018), who emphasized the importance of pod number and seed size in waterlogging tolerance selection. Likewise, biological yield per plant was strongly correlated with seed yield ($r = 0.957^{**}$), indicating that genotypes producing more biomass also tended to yield better. However, harvest index had only moderate association with seed yield ($r = 0.373$), reflecting the importance of efficient resource partitioning, not just total biomass accumulation. Interestingly, stress tolerance index was positively correlated with number of pods per plant ($r = 0.511^{**}$) and days to initiation of flowering ($r = 0.326^{*}$), suggesting that early flowering and pod formation are beneficial under waterlogged conditions, likely due to avoidance of peak stress periods. Oil and protein content showed weak and mostly non-significant correlations with yield traits, indicating that compositional traits may be governed differently under stress or might not directly relate to biomass accumulation and reproductive efficiency. The correlation matrix provides a comprehensive understanding of trait interdependence under waterlogged environments. Yield and its components especially number of pods, 100-seed weight, and plant height emerge as key selection traits for breeding waterlogging-tolerant soybean genotypes.

The Spearman's rank correlation analysis : The Spearman's rank correlation analysis among 15 traits of 45 soybean genotypes under waterlogging stress revealed important non-parametric associations that offer insights into trait interdependencies and selection strategies for stress resilience (Table 4). A strong positive correlation was observed between days to 50% flowering and days to physiological maturity (r = 0.828), indicating coordinated crop development. This relationship reflects consistency in genotypic growth patterns and is useful in predicting maturity based on flowering time under stress conditions (Popović, *et al*., 2012). Seed yield per plant exhibited moderate to strong positive correlations with days to 50% flowering (r = 0.346), biological yield (r = 0.145), and harvest index (r = 0.127), suggesting that genotypes that flower at an optimal time and accumulate higher biomass tend to yield better. This aligns with the findings of Flores-Félix, J. D. 2025), who reported that flowering duration and biomass allocation significantly influence yield performance under flooding stress. The harvest index showed a positive correlation with days to physiological maturity (r = 0.363) and days to 50% flowering (r = 0.357), implying that timely crop maturity contributes to better partitioning of biomass into economic yield. However, it had a negative correlation with protein content (r = -0.401), indicating a possible trade-off between seed composition and reproductive efficiency, as observed in earlier studies. The 100-seed weight had moderate correlations with seed yield (r = 0.201) and oil content (r = 0.294), suggesting that heavier seeds contribute not only to yield but also to oil accumulation, a desirable trait in oilseed breeding. A similar pattern was reported by Kavalgi, (2025), where seed weight was a key determinant of yield quality under stress conditions. Interestingly, plant survival rate had weak associations with most traits but showed a mild positive correlation with plant height (r = 0.183) and days to initiation of flowering (r = 0.293), indicating that early-flowering and taller genotypes may maintain better survival under saturated soil conditions. Traits such as days to 50% flowering, biological yield, 100-seed weight, and harvest index showed consistent associations with yield and stress indices, indicating their importance for selection in waterlogging-tolerant breeding programs.

Inter Cluster Distances of soybean genotypes : The Mahalanobis D^2-based inter-cluster distance analysis among four clusters of 45 soybean genotypes under waterlogging conditions revealed significant genetic divergence, which is essential for identifying promising parents for hybridization (Table 5). The maximum inter-cluster distance was recorded between Cluster III and Cluster IV (D^2 = 21.064), followed by Cluster I and Cluster II (D^2 = 19.351) and Cluster II and Cluster III (D^2 = 16.602). These large distances indicate that the genotypes grouped in these clusters possess considerable genetic variability for the traits considered under waterlogged environments. According to (Khan ,2014). higher inter-cluster distances suggest greater potential for obtaining superior transgressive segregants when genotypes from these divergent clusters are crossed. The minimum inter-cluster distance was observed between Cluster II and Cluster IV (D^2 = 13.935), indicating relatively lower diversity among the genotypes in these groups. Cluster I also showed a moderately close relationship with Cluster IV (D^2 = 14.642) and Cluster III (D^2 = 12.366), suggesting that these clusters share some similar traits or stress response mechanisms. These results highlight the utility of multivariate clustering in classifying genotypes based on performance under abiotic stress. Genotypes from clusters with higher genetic divergence particularly between Cluster III and

Cluster IV or Cluster I and Cluster II should be prioritized for use in recombination breeding programs aimed at improving waterlogging tolerance. This is consistent with the findings of Rhine, *et al*., (2010), who emphasized the importance of selecting genetically diverse parents to enhance the efficiency of selection and the likelihood of desirable trait expression in progeny.

Conclusion

Among 45 soybean genotypes evaluated under waterlogging conditions. Analysis of yield-contributing traits such as number of pods per plant, seed yield, 100-seed weight, biological yield, and harvest index highlighted genotypes like NRC 258, JS 21-72, AMS 2014-1, and RVSM 2011-35 as superior performers. Correlation analyses (Pearson and Spearman) demonstrated that traits such as plant height, number of pods, and seed weight were strongly associated with yield, indicating their reliability as selection indices under stress. Furthermore, inter-cluster distance analysis identified maximum genetic divergence between Cluster III and Cluster IV, offering valuable insights for strategic parent selection in breeding programs. The combination of phenotypic evaluation, statistical correlation, and multivariate analysis confirms the existence of exploitable diversity and provides a solid foundation for improving soybean resilience to waterlogging. These findings will aid breeders in developing high-yielding, waterlogging-tolerant soybean cultivars for stress-prone environments.

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